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Game Theory Approach to Product Service Systems

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Abstract

This conceptual paper discusses the application of game theory to Product Service System (PSS) research by highlighting the pros and cons in game theory in treating various aspects of PSS. To this end, we first describe the basic formulation in game theory, its usefulness and limitations and its potential applications in PSS. We then propose some ways of modeling three types of PSS: product-oriented PSS, use-oriented PSS, and result-oriented PSS using the game theory framework. Three studies that authors have so far conducted are presented as case examples: (1) a case addressing a member-type PSS, (2) a case of product lease service, and (3) a case of platform businesses. We explain how to apply our proposed modeling methods in the aforementioned cases.

Keywords: Equilibrium; Modeling; Willingness-to-pay per unit time

1. Introduction

Some manufacturers are now expanding their business focus from a conventional product selling to offering Product Service Systems (PSS). Although there are many reasons for that, one is due to the changes in customer needs and the ever-increasing competition. In the past, product ownership alone would satisfy customer needs, but nowadays both products and services are more desirable [1]. Another reason stems from the fact that technology development has been a contributing factor to profitability. However, because the current technology has been well developed, it will become more difficult to fully differentiate products in the market and gain the competitiveness based on the technological aspects alone. Therefore, differentiation by service, that is, service innovation, is somehow essential [2]. In addition, pressures from Circular Economy (CE) add another compelling reason for the shift [3][4]. PSS is recognized as a key enabler of CE as it contributes to the use of less material as the products being circulated.

PSS is defined by Goedkoop et al. [5] as

> *"… a system of products, services, networks of 'players' and supporting infrastructure that continuously strives to be competitive, satisfy customer needs and have a lower environmental impact than traditional business models."*

Since PSS research is yet to fully mature, despite the numerous studies (see review of PSS [6][7], for example), there are only a small number of papers adopting the game theory to model PSS. When considering service aspects, human factors are inevitably included and, we believe, game theory can appropriately deal with issues of human decision-makings.

In this conceptual paper, we discuss the applicability of game theory to describe various issues in PSS and propose several ways of modeling PSS using the game theory approach. In the next section, we will first explain a game theory formulation and discuss its advantages and limitations.

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Section 3 proposes the ways in which game theory can model the three types of PSS proposed by Tukker [8]. Section 4 gives some examples of game theoretic PSS studies. The paper concludes in Section 5, describing our lessons learnt and possible way forward in terms of research direction.

2. Game theoretic framework and Product Service Systems

This section discusses the application of game theory to PSS. First, we will explain how game theory generally formulates a decision-making situation. Second, we will describe its scope. After that, we will discuss the strengths and weaknesses of game theory in the context of PSS.

2.1. A general formulation by game theory

Game theory generally provides a framework of theoretical description about decision-making where multiple players are involved and have interdependent relations. For example, the normal form game, which is the simplest formulation, is composed of the following three elements：

- **Player**
  is an entity that makes decisions. It can be an individual like a consumer or an investor, and can also be an organization like a company, a group, a club, or a party; furthermore, a government or nation can be included. A large variety of entities can be expressed. Player's set is generally defined as $N = \{1, 2, \dots, n\}$.

- **Strategy**
  generally represents an action or action plan to play a game. Each player takes some action or action plan and then its outcome is determined. Letting s_i be a player i's strategy, $s = (s_1, \cdots, s_n)$ is called a strategy profile. A set of player i's strategies is defined as S_i.

- **Payoff**
  is a numerical expression of preference order over outcomes. Each player respectively has a different payoff function and it is generally defined as a payoff function, $f_i: S \to \mathbb{R}$, where S is a set of strategy profiles and defined as $S \equiv S_1 \times S_2 \cdots S_n$.

Accordingly, a normal form game is generally formulated as $\Gamma = < N, \{S_i\}_{i \in N}, \{f_i\}_{i \in N} >$. When N, S_i, and f_i are set as actual values/functions, it can express a certain concrete decision-making situation. As another form, game theory generally uses an extensive form game, where a game tree is used for expressing a game situation. Due to limitations of space, the detail formulation on extensive form game is not included.

2.2. Scope of game theory

As seen in section 2.1, a game theoretic framework is generally simplified and considers a situation where players choose actions from among predetermined alternatives. Thereby, various aspects are eliminated and abstracted. In addition, unrealistic extreme assumptions such as perfect rationality and complete information are imposed.

On the one hand, such an abstraction might be unrealistic, but on the other hand it can treat a broader scope of situations. This can be argued as the strength of game theory. Within such an abstracted description, game theory tries to derive its theoretical equilibrium and to understand the mechanism about its decision-making situation.

Among various equilibrium concepts, Nash equilibrium is the most basic one, which is defined as:

> *In n-person normal form game, $s^* = (s_1^*, s_2^*, \dots s_n^*)$ is called Nash equilibrium if for all $i \in N$ and for all $s_i \in S_i$, $f_i(s^*) \geq f_i(s_i, s_{-i}^*)$.*

Herein, s_{-i} stands for a strategy profile except player i's strategy, that is, $s_{-i} = (s_1, \cdots s_{i-1}, s_{i+1}, \cdots s_n)$. Roughly speaking, the meaning of Nash equilibrium state is that each player takes own payoff-maximizing action and has no deviation from the state.

By deriving Nash equilibrium, we can expect the state to be attained under rationality. Because people in reality do not necessarily take rational action or behave selfishly, the equilibrium state might sound meaningless. However, it can be regarded as being a consistent state in terms of incentive structure, so it shows a potential to act as a theoretical benchmark in considering a PSS structure.

In summary, the game theory indeed focuses on an abstract situation, but because from incentive point of view, game theory can clarify the fundamental mechanism behind them, it can be applied to model various issues in PSS.

2.3. Usefulness of game theory and its limitations

Game theory provides us a clear description of situations, so that it enables us to understand its theoretical structure. In addition, as mentioned in section 2.2, we can consider an issue of PSS as an incentive structure. Hereby we summarize its usefulness and/or advantages and limitations by separating them into the following subcategories.

2.3.1. Expression of player's preference prescribed by payoff function

In general, a payoff function is also called a utility function, and it defines preference that a player has. For a payoff function, a real number function is usually used, meaning that if a payoff value at a certain outcome is larger than that at another outcome, it denotes that the outcome with higher payoff is preferable. In general, preference is subjective and what people have in mind, so that it is difficult to define objectively. In game theory, however, a researcher assumes an imaginary person with a certain payoff function and accordingly defines preference compulsorily. Although this manipulation might sound unrealistic, it has strength in a scientific sense. This is because under a given preference, the structure of decision-making can be objectively demonstrated. This point is a very scientific approach.

On the other hand, such a deterministic way of describing preference would be one of the limitations of game theory. In the theory, preference is not changeable and is consistent over time. It is quite different from preference in a realistic sense. This is because it stems from axioms in preference: reflexivity, transitivity, and completeness. In the framework of decision theory, one think that those axioms are undoubtedly true without any proof. While this is powerful in some respect, it can be a weakness considering how much a real situation can be modelled directly.

Because human aspects to a large extent are included in PSS, the effectiveness of PSS can strongly depend on user's preference. In this sense, such a deterministic preference assumption is useful when researchers analyze how PSS works from a scientific point of view. In other words, it means that a researcher can concentrate on elucidating the mechanism of PSS under a situation that various types of preference are given.

2.3.2. Equilibrium concepts

As already mentioned in section 2.2, equilibrium analysis is a major method to understand situations modelled by game theory. This can be an advantage because it can give us a clear understanding and insights. Since equilibrium is only a static state, it is not appropriate to analyse the dynamic process to reach the equilibrium. In general, game theory does not consider how people behave until the equilibrium point is reached. In case of applying to PSS studies, researchers must be aware of this point.

Nash equilibrium is composed under some sort of specific theoretical world. Therefore, as unreality is often criticised, it cannot represent the real world. Even in the world of physics, the same thing would be true. In physics, one solve a motion equation and understand its dynamics: for example, an object flies with an ideal parabolic line being drawn. However, in reality, due to air resistance, an object does not fly through an ideal parabolic line. Similarly, Nash equilibrium in game theory is an ideal state, so it is natural that it does not perfectly represent the real world. Therefore, such a way of thinking can be applied in the case of PSS studies.

2.3.3. Expression of Outcome

A result of game is represented as a form of outcome, which is a resultant state after all players have made their decisions. Mathematically, it is a vector of actions taken by players or a vector of payoffs that corresponds to actions taken by them. In terms of objective expression, it would become an advantage. A vector of actions can mean an observable state in PSS, so it is understandable and tractable.

However, such an expression does not have enough freedom and it would be insufficient to express a complicated PSS.

2.3.4. Treatment of information structure

In game theory, information is treated in a well-organized manner, e.g. (im)perfect information, (in)complete information, information set, common knowledge, private information, etc., but most of them are simplified to fit a mathematical formulation. In PSS, complex information structure is needed. Thus, although mathematically sound, game theory has limitations in treatment of complex information structure.

2.3.5. Incorporation of probabilistic events

Game theory is strong in dealing with probabilistic events. For example, player's strategy can be expressed by probability, which is called mixed strategy and can be a theoretical base. In addition, a probabilistic decision, which is called nature's move, is represented as a special node in a game tree: the node is not attributed by any player and its decision is determined simply by probability. Moreover, since a base of game theory is expected utility, probability is intrinsically a part of game theory.

In addition, game theory provides a framework of Bayesian game which can treat a situation with incomplete information. Usually, private information like a type is used and a type is distributed with some probability. Letting his/her own type be an observation, Bayes probability of other player's type can be calculated. With the posterior probability, the expected payoff can be determined and then Nash equilibrium can be derived. This is called Bayesian Nash equilibrium. Even if such a probabilistic situation is introduced, game theory can manipulate decision-making situations well.

In PSS studies, it is necessary to model a PSS structure as a probabilistic event in some cases. Game theory approach will therefore be useful in this respect.

3. Ways of modeling PSS with game theoretical approach

This section discusses how three types of PSS [8] (product oriented PSS, use-oriented PSS, and result-oriented PSS) can be modelled in game theoretic framework.

3.1. Product-oriented PSS

According to Tukker [8], product-oriented PSS is the one whereby:

> "... *the provider not only sells a product, but also offers services that are needed during the use phase of the product*".

This situation can thus be regarded as a contract between the provider and its customers, so that such a situation can be modelled as a contractual decision-making among players in game theory. However, after the contract is signed, some sort of service process during the use phase is provided. It means that expected/unexpected events will occur after the contract, so that a sequential game like Fig. 1 is appropriate, where a contract decision is represented by a node and then some events in use phase continue as subsequent nodes.

Consider a maintenance contract, for example. Here we are uncertain when a product will fail, meaning an element of risk needs to be included. In that case, probabilistic events may be incorporated into the model. In game theory, generally, such a probabilistic event can be described as a nature's move. Especially in case of product failure, its rate can be approached using some probabilistic distribution and it is relatively easy to incorporate such a probabilistic event because game theory can treat decision making with probability.

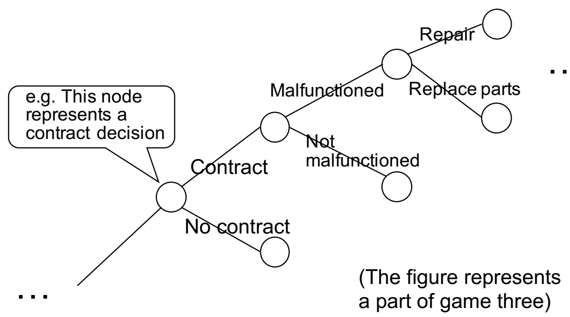

Fig. 1. A modelling way of product-oriented PSS with game theory.

3.2. Use-oriented PSS

In general, product lease or sharing is applicable to this type of PSS. One of the characteristics in this PSS type is that the provider owns the products [8] and only product functionality is sold to the customers. In the game theoretical framework, this situation can be described as a decision on the how long to use the function of a product for, e.g. how many hours a car is being rented out. Even if a player's decision variable is of a continuous value, a game theoretical framework works well, although it is often assumed that a set of possible actions that a player can take is a finite set. If a set of actions is infinite, the existence of Nash equilibrium cannot be theoretically assured [9].

To model this situation, we propose an idea of willingness-to-pay per hour (WTP/h) or per other unit time. The term WTP (often used in economics) explains how much a player is willing to purchase the product at most. On the other hand, in case of WTP/h, the same idea is applied to service situation. So WTP/h means an amount of money that a player is willing to pay for a service in one hour. Nonetheless, in reality, WTP/h is decreasing as time goes by (Fig. 2). For example, if considering a case that you want to rent a car for 5 hours, you would feel another hour after 5 hours past is less important because 5 hours are enough. It means WTP/h for an hour from 4 to 5 hour use is higher than that from 5 to 6 hour use as shown in Fig.2.

To consider the use-oriented PSS in a game theoretical framework, the idea of WTP/h should be reflected in the payoff functions.

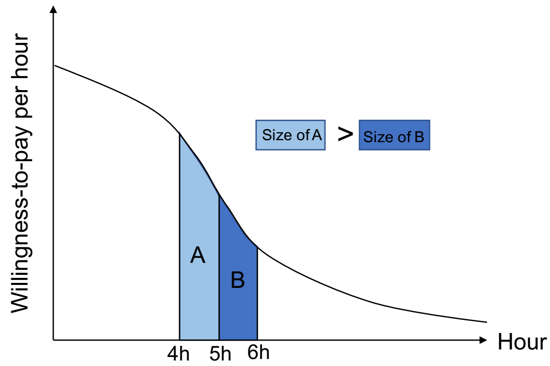

Fig. 2 Decreasing willingness-to-pay per hour.

3.3. Result-oriented PSS

As discussed in section 2.3, game theory uses a form of outcome, wherein all player's actions are described as a vector. Also, in game theory, an outcome means a resultant state after all players took respective actions. It can be also regarded as a state where all services have completely been provided. Tukker [8] used the outsourced service as an example of this type of PSS. So, a form of outcome is appropriate to the result-oriented PSS, as a state after service was completed, is the primary concern. A game theoretical framework can directly be used in this PSS but a model should include a description how the service precisely fulfils the required quality or specifications.

A remarkable difference from the modelling of product-oriented PSS is that risk is not included. For example, in case of maintenance contract scheme as a product-oriented PSS, it is not certain when a product will fail and to what extent. So this is a risk. On the other hand, in an example of outsourced service as the result-oriented PSS, all process is outsourced, so that the provider will bear all the risks. A qualified result only is provided with users in this result-oriented PSS.

3.4. Summarizing ways of modelling PSS

In section 3, we have so far discussed how to model the three types of, although when modelling them using the game theoretic framework, it would be difficult to clearly treat them as distinct types, and thus, a combined way of three modeling types would be required. It is also important that by observing PSS in reality, the situation can be simplified and abstracted into a game theoretic situation.

4. Case examples

This section presents several examples where we apply game theory to service-related issues. The first one is a study addressing the member-type PSS [10][11]; the second one is a case of product lease service [12]; and the third one is the platform business [13][14].

4.1. Membership-type service

In our previous studies [10][11], membership-type service has been modelled using the game theory approach. Herein, the decision-making processes between a service provider and service receivers are addressed. Fig. 3 depicts an overview of the model. While a membership service is provided by the service provider, the service receivers join the group members and enjoy services. If the service receivers join the group members, then they are able to use the services at discounted prices as a membership privilege. Even if receivers do not join, they can use services at a normal price. This study, in addition to Nash equilibrium analysis, used multi-agent simulation and human subject experiments and compared performances between complete and incomplete information cases.

The way to model PSS as described in section 3.1 will be applied here. As shown in the figure, service receivers make decision of joining membership; and after that, they decide whether to use a service repeatedly. The structure is the same as a contract case explained in section 3.1.

This model is, indeed, simplified but can be applicable to several PSS cases in reality. For example, sports clubs and reward programs share this type of structure.

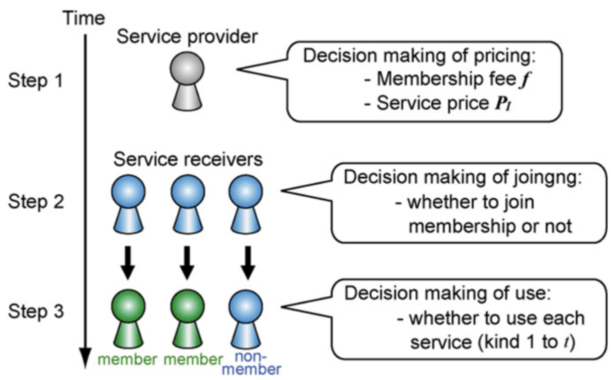

Fig. 3. An overview of membership-type service (Source: [10])

4.2. Product lease service

As an extension to the above case, a product leasing service model is hereby constructed [12]. In the model, a manufacturer decides a service price per unit time and product functionality level of a product. Each consumer makes own decision whether to use this service and, if so, for how long. The customer decides the duration of product use. The consumer's willingness-to-pay was defined as shown in Fig. 4. Especially in this study, a main target was to clarify conditions that product lease service is more profitable than a product selling case by deriving the Nash equilibrium.

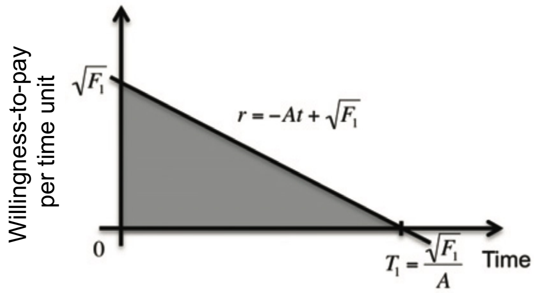

Fig. 4. Definition of willingness-to-pay in car sharing model (Source: [12])

The formulation of willingness-to-pay in the model is in accordance with a modeling of use-oriented PSS mentioned in section 3.2. A decreasing function presented in Fig. 4 is used to express WTP per time unit. Thereby, consumer's payoff function is defined as

$$f_i = \int_{r \geq p} r(t) - p\, dt,$$

where r and p stand for WTP per unit time and service price, respectively.

This type of modeling ways is widely applicable to various situation of PSS. A point here is to introduce the idea of WTP per unit time. It could widen the area that game theory can address in PSS modelling.

4.3. Platform-business

Our last case [13][14] is a model of platform-type business, which includes players of four kinds: content developers, the platform provider, the device manufacturer, and consumers. The content developers produce some content that constitutes service components and which cannot work per se. The device manufacturer produces some devices on which the contents work, representing the product components. The platform provider provides a sort of a platform which connects the device and the contents, e.g. interfaces for microprocessors, operating systems for PCs, a unified standard, etc. Accordingly, the platform provider issues licenses to content developers or the device manufacturer. Each player's decision and product flow are depicted in Fig. 5.

In the formulation of this model, an outcome is described as the decision that consumers make about what device and contents to purchase, implying that this model adapts a modelling of result-oriented PSS explained in section 3.3. However, the use phase on the platform is an important aspect in reality, e.g. how users consume contents on the platform, how they interact with manufacturers and/or other users, etc. Therefore, a combined modelling of product-oriented and use-oriented PSS would also be essential. The studies [13][14] do not address such aspects but it shall be considered as future work.

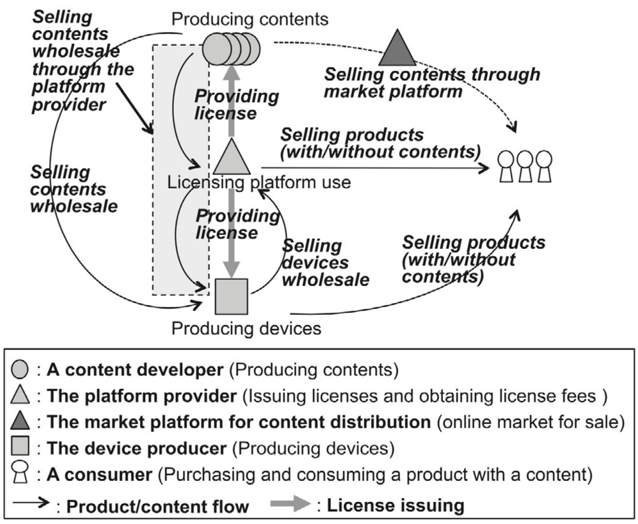

Fig. 5. A basic model framework of platform PSS structure (Source: [13])

5. Discussion and concluding remarks

This article discussed the potential applications of game theory to PSS. From a theoretical point of view, its usefulness can be demonstrated. However, there exists an open issue, which is about “co-creation”. In PSS, it is often said that co-creation should be a key for success [15]. Such a co-creation can be realized through dynamic interactions amongst stakeholders. Game theory, however, defines a mathematical framework in a definite manner and therefore it does not directly address dynamic interactions that co-creation essentially has. Nonetheless, game theory showed a potential contribution in constructing some sort of theoretical benchmark about co-creation. In addition, the idea of functional products [16] fits well into an expression of equilibrium, so that has a possibility to discuss co-creation in terms of game theory. We need to consider ways of addressing this aspect of co-creation, including practical ways of experimenting with such a model [17], particularly from a game theoretic point of view.

To our knowledge, despite the numerous studies in modelling PSS, e.g. [18], the application of game theory in PSS appears to be scarce. As PSS incorporates the element of human factors, game theory can be useful. We have discussed the strengths and the weaknesses of game theory and we have also discussed its applicability. Based on the discussion, several ways of using game theory to model PSS have been proposed in this paper. The first is applied to product-oriented PSS, where the importance of the description of contract in a game theoretical framework has been demonstrated. The second is applied to model the use-oriented PSS. For that, we argue that it is necessary to consider the idea of WTP per unit time. Finally, the third is applied to model the result-oriented PSS, in which the conventional game theoretic way of modelling can be applicable.

To conclude, game theory adopts a simplified and abstracted form of description, and it can be one of the worthwhile tools that can help understand many types of decision-making situations, especially in PSS. We hope to see the growth of PSS work using game theory in the near future.

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